

Summary of Research NAG-1-2167

The following compilation documents significant deliverables provided by the Principal Investigator, Dr. Dave Riggins, under this grant. Note that this summary is extracted from a larger report provided to the Hyper-X office last year at the conclusion of the grant.

JANNAF Activities

The following pages document current status of the ongoing JANNAF Scramjet Test Standards activity from the standpoint of the Analysis Sub-Group of which the PI was requested by NASA to be chairman. Also included are some representative contributions to date from the Principal Investigator relating to this activity.

JANNAF Analysis sub-group

status key:

- 0 nothing provided as of yet
- 1 storyboard provided
- 2 short writeup provided
- 3 complete rough draft provided

Paragraph	Title	Status	POC
2.2	Engine Station Designations	1 (figure)	Beckel/Riggins
2.3.1	Mission Parameters/Defs	1	Riggins
2.3.2.1	Def of Combustion Efficiency (energy-based)	3	Riggins
2.3.2.2	Def of Combustion Efficiency (mass flux-based)	3	Riggins
2.3.2.3	Deriving Combustion Efficiency from Experimental Data	3	Riggins
2.3.2	(other sub-sections/component 0 parameters still to be written)		Riggins
2.3.3.1	Engine Performance	3	Riggins/Bowcutt/Davis
2.3.3.1.1	Def of engine reference line	3	"
2.3.3.1.2	Def of propulsion coord system	3	"
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2.3.3.4	Durability and Life-Cycle + subsections	0	Garrard (recently assigned)
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2.3.2 Required Component Parameters and Definitions

2.3.2.1 Definition of the Combustion Efficiency (Energy-Based)

I. Preliminary Comments

The combustion efficiency is simply a normalized parameter, i.e.,

$$\eta_c = \frac{\text{'actual out'}}{\text{'best out'}}$$

and since the denominator ('best out') is entirely relative (depending on the assumptions of what constitutes 'best' - what level of equilibrium model is used, complete reaction, details of pressure value used in equilibrium model, etc.), the denominator of η_c is entirely a user-dependent reference quantity.

It is the numerator ('actual out') which the experiment AND the cycle code actually produce and need. When η_c is fed into a cycle code, the code simply scales away the denominator using a pre-programmed method to calculate the 'best out', in order to get to the real input it needs - which is the numerator (best viewed as corresponding to the mass fractions of the reacting mixture - i.e., the chemical composition - at the station of interest).

Hence, simply viewing η_c as 'experimental data' for input into a cycle code is incorrect; the denominator calculation MUST be matched between the analysis of the experiment and the cycle code into which the η_c is to be input. Otherwise, the 'actual out' (the real input) is scaled incorrectly. Even more obviously, if the cycle code utilizes a 'mass-flux based' combustion efficiency definition and one inputs an 'energy-based' combustion efficiency, the corresponding scaling is completely in error.

This is also true for the case where a one-dimensional or cycle analysis is used to produce an η_c estimate from matching the wall pressure integral of an experiment. For such a case, in order to have any meaning, it is necessary for that η_c estimate to be accompanied by information on the level of cycle code used, the chemistry model used, the exact definition of the denominator (i.e., what level equilibrium or complete reaction mechanism was used), etc. Without complete information, a person needing to use that η_c value in any subsequent analysis is not going to be able to get back to the real information which resides in the numerator of the η_c definition (the 'actual out').

II. Energy-Based Definition of η_c

$$\eta_c = \frac{h(T_{imix}, \alpha_{mix}'s) - h(T_{imix}, \alpha_e's)}{h(T_{imix}, \alpha_{mix}'s) - h(T_{imix}, \alpha_{complete\ reaction}'s)} \quad (1)$$

α_{mix}	=	mixed initial (reactant) species mass fraction (based on \dot{m}_{fuel} , \dot{m}_{air})
T_{imix}	=	static temperature of mixed (initial) reactant species
α_e	=	actual mass fractions of product species at combustor station of interest
$\alpha_{\text{complete reaction}}$	=	mass fractions of product species assuming complete reaction
h	=	static enthalpy per mass
	=	$\sum_{\ell=1}^N \alpha_\ell \left\{ h_{o_{\text{ref}}} + \int_{T_{\text{ref}}}^{T_{\text{imix}}} c_{p\ell} dT \right\}$
		N = number of species

III. Other Comments/Issues

- A. The choice of T_{imix} rather than a reference temperature (say STP) in the recommended definition of combustion efficiency is driven here by the need to exactly specify the heat of reaction for a given system. Note that the recommended combustion efficiency here is identical to that proposed in NASP TM 1107 "Hypersonic Combustion Kinetics," with the exception that, in the latter reference, the temperature choice is considered arbitrary (but normally chosen as STP) with the caveat then given that the choice of temperature influences η_c in an arbitrary (but small) fashion. Here, by choosing T_{imix} , (which is readily calculated in any event), an exact representation of the heat-of-reaction-based combustion efficiency is obtained.
- B. The calculation of T_{imix} is easily obtained from knowledge of inflow and fuel injection conditions. A constant area, frictionless wall, and adiabatic step solver can be constructed which conserves mass flow rate, stream thrust, and total enthalpy flux. From this, mixed conditions can be numerically computed.
- C. The denominator of the recommended combustion efficiency can be computed utilizing an equilibrium process rather than using complete reaction. However, if this is done, care must be taken to specify fully the type and degree of equilibrium solver used in the definition so that the key information (the numerator) can then be accessed from the η_c value.
- D. The definition of complete reaction for fuels other than hydrogen must be defined based on the specific fuel-air chemistry relevant to the situation under analysis.

2.3.2.2 Definition of the Combustion Efficiency (Mass-Flux Based)

An alternative definition of combustion efficiency can be given as follows:

$$\eta_c = \frac{\Phi_{\text{reacted}}}{\Phi_{\text{injected}}} = 1 - \frac{\Phi_{\text{unburned fuel}}}{\Phi_{\text{injected}}}$$

where

$$\Phi_{\text{injected}} = \frac{\text{mass flow rate of fuel injected}}{\text{mass flow rate of fuel required for stoichiometric combustion with available oxidizer}}$$

$$\Phi_{\text{unburned fuel}} = \frac{\text{mass flow rate of unburned fuel}}{\text{mass flow rate of fuel required for stoichiometric combustion with available oxidizer}}$$

$$\Phi_{\text{reacted}} = \Phi_{\text{injected}} - \Phi_{\text{unburned fuel}}$$

2.3.2.3 Deriving Combustion Efficiency from Experimental Data

In the context of cycle analysis, a computed value of combustion efficiency represents a single-valued representation of the reaction state of the flow at a given station; the value is directly calculated from the known species mass fluxes at that station. Since the species mass fluxes in a cycle code themselves are a result of some assumed kinetics model (complete reaction, equilibrium, finite-rate, number of reactions, etc.), the combustion efficiency value output from a cycle code is always dependent on the particular kinetics model used to generate it (as well as whether it is energy or mass-flux based).

It is common practice to derive an estimate of the combustion efficiency from experimental combustor data which includes a wall pressure distribution. This is done by incorporating a cycle analysis program into the data reduction effort. Principle inputs for the cycle code are the combustor inflow conditions, the combustor area distribution, the wetted perimeter distribution, wall temperature, friction coefficient, and the wall static pressure distribution. At each numerical step in the program enough fuel is allowed to react in order to just match the measured wall pressure. The mass fluxes of species at that station are then used to calculate the combustion efficiency, whether energy or mass-flux based. Again, this value of combustion efficiency output is entirely dependent on the particular kinetics model within the cycle code used for analysis of the data. In order to enforce standardization, combustion efficiency obtained in this fashion from experimental wall pressures should be derived using the lowest level kinetics model possible – complete reaction. If more complex methods are used in the analysis, information on the details of the kinetics model used must be provided along with any values of combustion efficiency given.

2.3.3.1 OVERVIEW OF FORCES AND FORCE/MOMENT DEFINITIONS FOR SCRAMJET ENGINES

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2.3.3.1 OVERVIEW OF FORCES AND FORCE/MOMENT DEFINITIONS FOR SCRAMJET ENGINES

Consider a rigid aerospace vehicle in flight through the atmosphere (see Fig. 1). There is some resultant net force vector, \vec{F}_R , which is associated with the summation of all fluid dynamic pressure and shear stress force distributions on all wetted surfaces of the vehicle (both internal and external to the engine). This net fluid dynamic force vector is inclusive of the conventionally defined lift, drag, and thrust forces on the vehicle which, however defined, simply represent components of this overall force vector. The wetted surfaces on which pressure and shear forces act include all internal surfaces of fuel or propellant injector lines within the structure, going all the way back into and including the surfaces of fuel/propellant tanks. Instantaneous vehicle acceleration, cruise (equilibrium) or deceleration depend on i) the magnitude and direction of the overall fluid force vector, ii) the weight force vector, and iii) any externally applied forces imposed on the vehicle (i.e., external to the vehicle such as an off-board electromagnetic force field). In the absence of the latter, the instantaneous motion of the vehicle is governed by:

$$m_{\text{veh}} \frac{d\vec{V}_{\text{veh}}}{dt} = \vec{F}_R + \vec{W} \quad (1)$$

Furthermore, if the line of action of the fluid force vector does not intersect the vehicle center-of-gravity, there is an instantaneous moment causing rotation of the vehicle about the center-of-gravity.

2.3.3.1.1 DEFINITION OF ENGINE REFERENCE LINE

Assume that there is some distinct geometric line (x axis) running through the vehicle center-

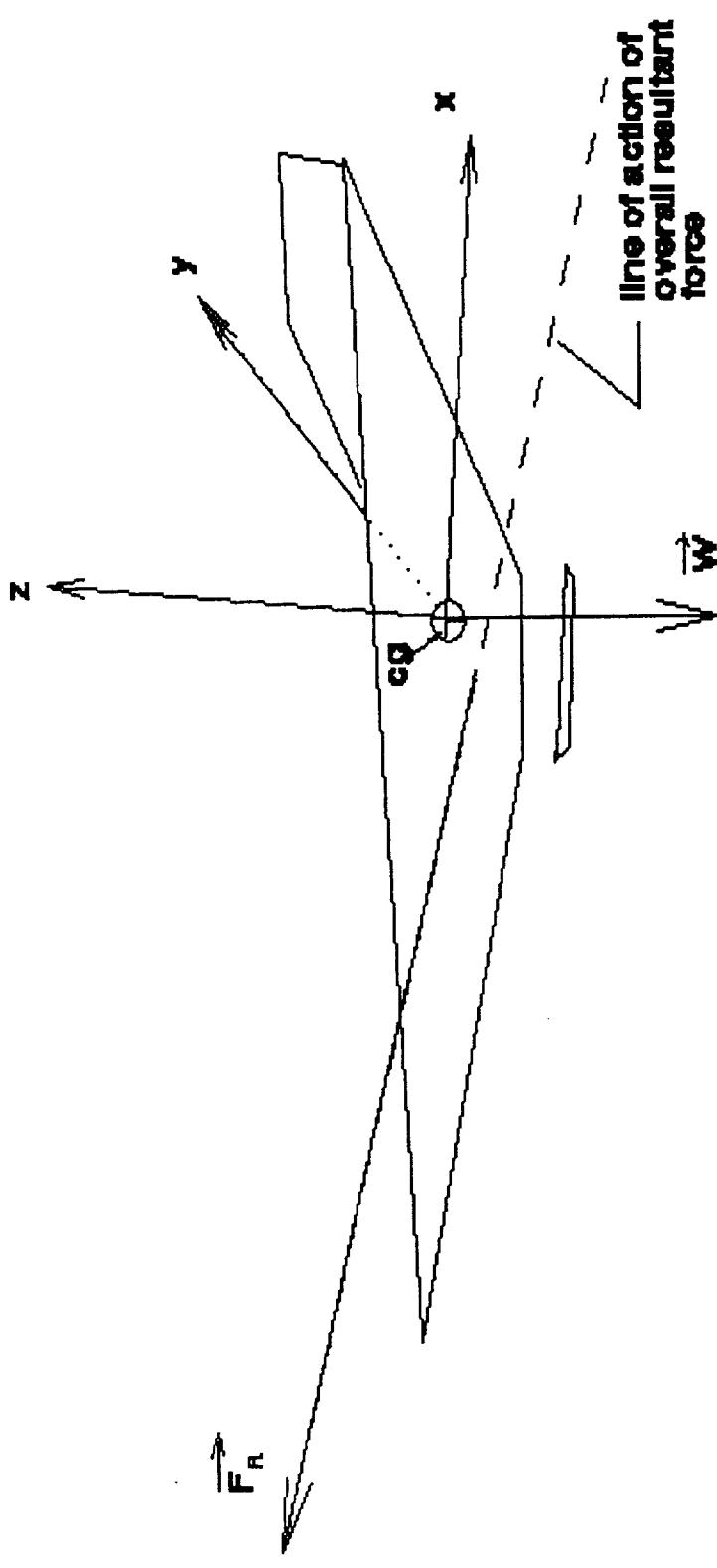


Figure 1: Force schematic for hypersonic vehicle in flight

of-gravity and defined with respect to the engine frame. This line is generally longitudinal (axial - denoted 'x') with respect to the general lines of the internal configuration of the engine frame (see Fig. 2); positive x is measured from left to right along this line (i.e., out the vehicle tail). There are planes perpendicular to this line which can be identified as the inlet face-plane (o) and the nozzle exit-plane (6) of the engine.

2.3.3.1.2 DEFINITION OF PROPULSION COORDINATE SYSTEM

The z axis is defined as that line with origin at the center-of-gravity (cg) which is formed by the intersection of the plane orthogonal to the x axis with the symmetry plane of the vehicle. Let positive z be as shown in Fig. 1. The y axis with origin at the cg is then defined by the usual right-hand system such that positive y is in the direction of the right wing of the vehicle (as shown).

2.3.3.1.3 DEFINITION OF ENGINE THRUST, F_x

The engine net thrust is formally defined as that component of the overall resultant force vector which is parallel to the engine reference line and which is associated with all pressure and shear force contributions on all engine wetted surfaces between the inlet face-plane and the nozzle exit-plane. Positive thrust is measured in the negative x direction. Hence:

$$F_x = - \int_0^6 (P_w \hat{n}_x + \tau_{wx}) dS_w \quad (2)$$

S_w = total wetted surface area of the engine between inlet face-plane and the nozzle exit-plane

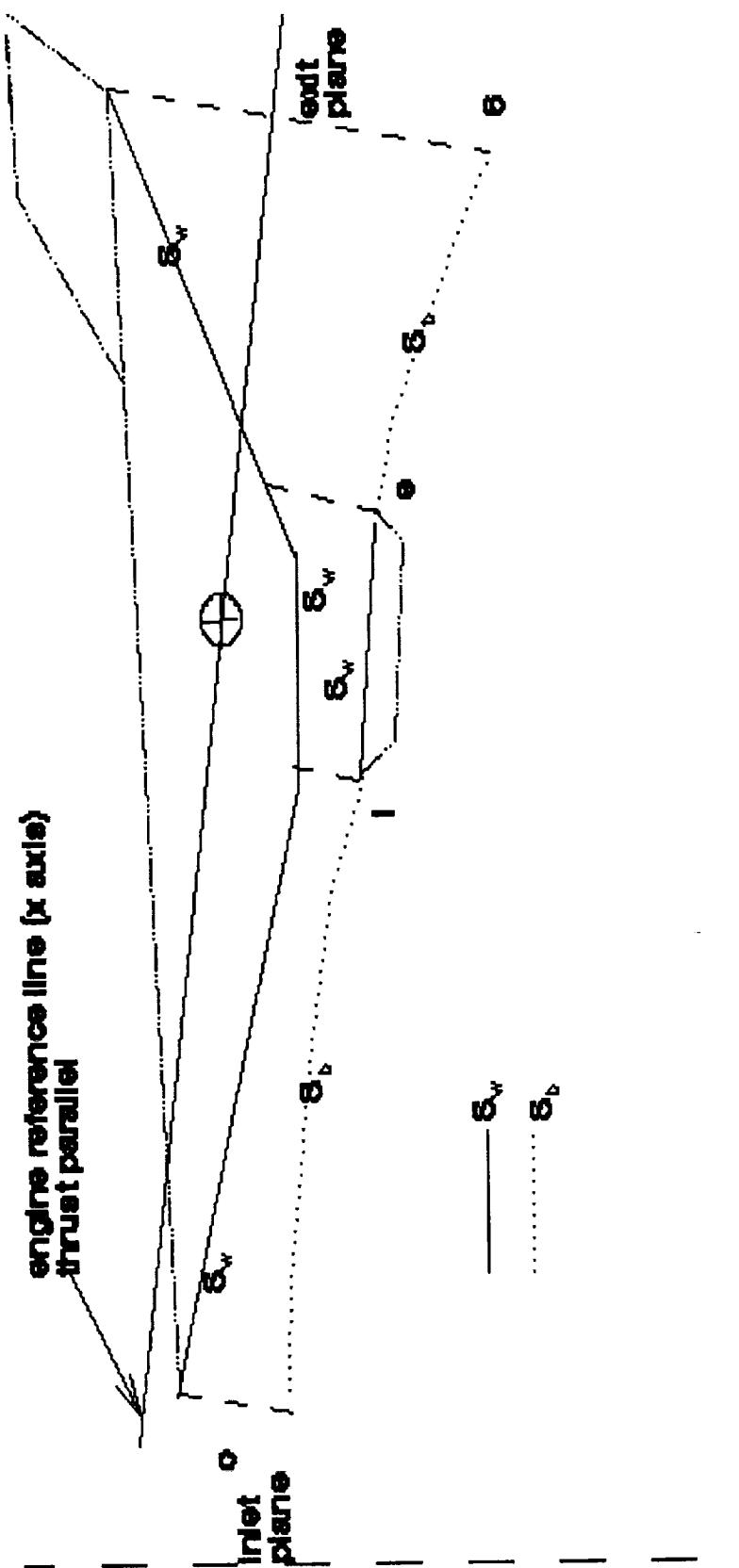


Figure 2: Engine reference line and engine control volume schematic

- P_w = fluid dynamic static pressure acting on wetted engine surface
 τ_{wx} = axial component of shear stress on wetted engine surface (positive when flow is moving in positive x direction)
 \hat{n}_x = the axial component of the 'unit normal' directed outward from the fluid (into the engine structure) along the wetted surface
 o = inlet face-plane
 e = nozzle exit-plane

2.3.3.1.4 THRUST DEFINITION ISSUES

Thrust Force on an Enclosed Streamtube

From the standpoint of steady quasi-one-dimensional analysis, the axial force felt by all wetted internal surfaces (side boundaries) surrounding an enclosed streamtube (shown in Fig. 3) from inflow plane, i , to outflow plane, e , (perpendicular to x) is by the momentum equation as follows:

$$F'_x = \dot{m}_e u_e + P_e A_e - \dot{m}_i u_i - P_i A_i = - \int\limits_i^e (P_w \hat{n}_x + \tau_{wx}) dS_w \quad (3)$$

where u is the velocity, \dot{m} is the mass flow rate, etc.

This is the raw axial force transmitted to the solid structure surrounding the fluid (i.e., it is the force measured in a direct-connect test of the internal configuration of an engine). This expression includes the axial force contribution of all fuel/propellant injection systems between i and e . It is valid for rocket engines (with $\dot{m}_i, A_i = 0$) as well as air-breathing jet engines.

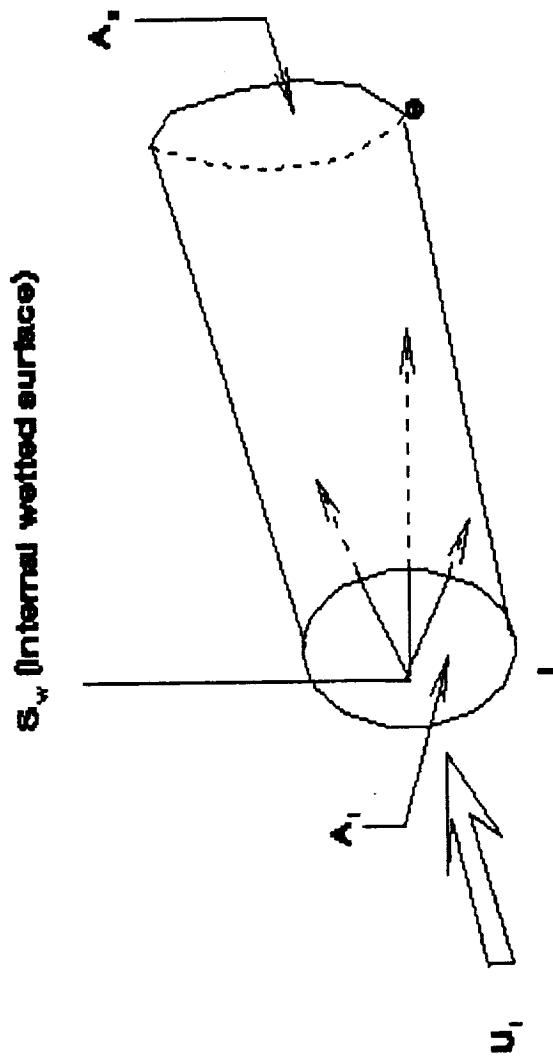


Figure 3: Enclosed streamtube schematic

Conventional Definition of Thrust Force on Enclosed Streamtube

If an external axial force component resulting from constant ambient pressure (P_i in this case) acting on the external surfaces from i to e is assumed, then the conventional definition of engine thrust (in fact developed from consideration of a low-speed engine on a thrust stand at static conditions) is obtained as:

$$F_x^{II} = \dot{m}_e u_e - \dot{m}_i u_i + A_e (P_e - P_i) \quad (4)$$

Note, however, that this definition includes the assumption of a uniform P_i acting on external surfaces from i to e ; if this definition is used, care must be taken to account for this assumption for a vehicle/engine NOT at static ($M_\infty = 0$) conditions. For such a case, all external aerodynamic pressure force terms should be based on $P_{act} - P_i$ ('gauge'). As a cautionary note, external CFD is often used which works in terms of absolute pressures (not gauge pressures). It is always necessary to correctly match experimental and analytical force definitions as well as internal force definitions and external force definitions.

Definition of 'Additive' Drag (Scramjet Engine)

A scramjet engine which is integrated into the airframe is generally considered to be composed of the entire underside of the vehicle with the exception of the underneath side of the cowl. Based on this consideration, a control volume from vehicle leading edge to vehicle trailing edge can be drawn which encompasses all fluid entrained and processed by the internal part of the engine. There generally exist surfaces of this control volume which are not bounded by any solid (wetted) surfaces of the vehicle but are instead simply fluid-fluid interfaces. Such surfaces usually exist upstream of

the cowl leading edge and downstream of the cowl trailing edge.

- i) Consider first a podded (conventional) engine as shown in Fig. 4: the actual thrust force transmitted to the engine structure (along the internal wetted surfaces) by the fluid is given by (3) as:

$$F_{x_{\text{actual}}} = \dot{m}_e u_e + P_e A_e - \dot{m}_i u_i - P_i A_i \quad (5)$$

However, it is often considered advantageous to write the thrust expression in terms at o (free-stream) rather than at i. If there is acceleration or deceleration of the entering fluid streamtube upstream of i, such as shown in the figure, there is a corresponding change in flow conditions from o (free-stream) to i. The so-called 'uninstalled' thrust (not including external drag) is written here as

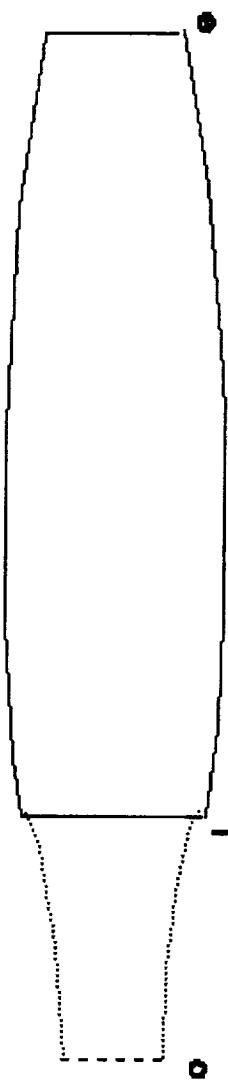
$$F_{x_{\text{uninstalled}}} = \dot{m}_e u_e + P_e A_e - \dot{m}_o u_o - P_o A_o \quad (6)$$

This defines the overall force resulting from differential pressure and shear forces on all boundaries of the capture streamtube from o to e, i.e., including the fluid-fluid interfaces external to the engine (from o to i). However, forces on such interfaces cannot contribute to the actual force experienced by the solid wetted surfaces of the engine from i to e. Hence, the additive drag is readily defined by subtracting the actual thrust from the uninstalled thrust (where $\dot{m}_i = \dot{m}_o$ for steady flow):

$$D_{\text{add}} = F_{x_{\text{uninstalled}}} - F_{x_{\text{actual}}} = \dot{m}_o (u_i - u_o) + P_i A_i - P_o A_o \quad (7)$$

This term simply represents the inevitable reduction in thrust from the uninstalled thrust definition due to external acceleration or deceleration of the captured streamtube.

Figure 4: Conventional engine sketch showing upstream deceleration of engine capture streamtube



ii) Now consider a hypersonic engine defined as encompassing the entire lower vehicle surface from vehicle leading edge (o) to vehicle trailing edge (6) with an internal engine configuration from i to e (Fig. 2). The capture streamtube is enclosed with a control surface as shown in the sketch. Planes at o and 6 are perpendicular to the engine reference line as previously defined. Let u be the velocity component along this line.

Define the total axial force felt by the side boundaries of the capture streamtube from o to 6 as

$$F_{x_{o-6}} = \dot{m}_6 u_6 + P_6 A_6 - \dot{m}_o u_o - P_o A_o \quad (8)$$

Note that if the wetted (solid) surfaces of the vehicle completely enclosed this streamtube from o to 6 (corresponding to a cowl extending from o to 6), this expression would represent the thrust actually delivered to the vehicle by the engine. However, there are portions of the flowpath which are not bounded by solid surfaces (from o to i 'underneath' the forebody and from e to 6 'underneath' the afterbody). The forces on these surfaces contribute to $F_{x_{o-6}}$ but do NOT operate on the vehicle - i.e., they do not contribute to the actual thrust force felt by the vehicle. Hence, the following expression can be written:

$$F_x = \dot{m}_6 u_6 + P_6 A_6 - \dot{m}_o u_o - P_o A_o - D_{(o \text{ to } i)}^{\text{add}} - D_{(e \text{ to } 6)}^{\text{add}} \quad (9)$$

F_x = delivered thrust (axial force experienced by wetted surfaces of engine from o to 6) (positive in the -x direction)

where $D_{(o \text{ to } i)}^{\text{add}}$ is the axial component of the force associated with the upstream (o to i) portion of the streamtube not bounded by any wetted surface of the vehicle and, similarly, $D_{(e \text{ to } 6)}^{\text{add}}$ is the axial

component of the force associated with the downstream (e to 6) portion of the streamtube not bounded by any wetted surfaces of the vehicle.

iii) The formal integral definitions of the additive drag components for an air-frame integrated scramjet are given below:

$$D_{\text{add}}^{\text{out}} = - \int_0^i (P_b \hat{n}_x + \tau_{bx}) dS_b \quad (10)$$

$$D_{\text{add}}^{\text{in}} = - \int_e^6 (P_b \hat{n}_x + \tau_{bx}) dS_b \quad (11)$$

where S_b is that portion of the capture streamtube not bounded by vehicle/engine wetted surfaces (i.e., S_b encompasses all fluid-fluid interfaces of the streamtube boundary) and τ_b is the shear stress acting on S_b .

2.3.3.1.5 INTEGRAL DEFINITION OF THRUST

From the previous discussion, the formal definition of thrust (eq. 2) can be presented (rewritten) in integral form:

$$F_x = \int_6^i [\rho u^2 + P] dA_6 - \int_0^i [\rho u^2 + P] dA_0 + \int_0^i (P_b \hat{n}_x + \tau_{bx}) dS_b + \int_e^6 (P_b \hat{n}_x + \tau_{bx}) dS_b \quad (12)$$

2.3.3.1.6 MEASUREMENT OF THRUST

This completes the formal comprehensive definition and discussion of the absolute thrust force experienced by a hypersonic vehicle with an airframe-integrated scramjet engine. It follows that

there are three ways to measure the thrust of the engine:

- a) direct measurement by thrust-stand
- b) complete differential description of pressure and shear distributions on all wetted surfaces (internal and external) (eq. 2)
- c) complete differential description of capture streamtube density, velocity, and pressure on inflow and outflow planes AND complete differential description of pressure and shear force distributions on ALL fluid-fluid interfaces (free-surfaces) of the capture streamtube (eq. 12).

In the total absence of experimental (or numerical) errors and uncertainties, these three methods yield completely equivalent values of thrust.

2.3.3.1.7 FUEL CONTRIBUTIONS TO THRUST

The definitions of engine thrust given in eq. (2) and eq. (12) are inclusive of ALL pressure and viscous forces on the entire wetted surface of the engine, including internal fuel injector lines and the envelope of the propellant tanks themselves. The component of the overall force vector associated with the fuel injector tanks and lines can itself be calculated from Newton's law as:

$$\bar{F}_{\text{inj}} = \int_{S_{\text{orifice}}} \rho_{\text{inj}} \bar{V}_{\text{inj}} (\bar{V}_{\text{inj}} \cdot \hat{n}) dS_{\text{orifice}} + \int_{S_{\text{orifice}}} P_{\text{inj}} \hat{n} dS_{\text{orifice}} \quad (13)$$

where the surface of the fuel injection orifice is now treated as part of the wetted surface of the engine in defining the direction of \hat{n} (see Fig. 5).

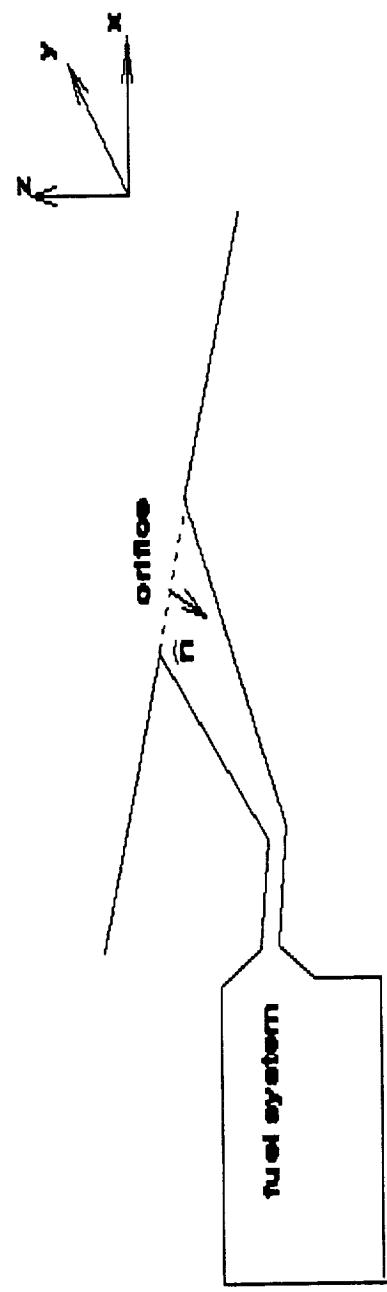


Figure 5: Unit normal orientation for fuel injection orifice

Hence, if the fuel system wetted surface areas are neglected in the integral definition of the wetted surface areas in eq. (2), the expression for the thrust becomes:

$$F_x = - \int_0^6 (P_w \hat{n}_x + \tau_{wx}) dS_w - F_{x_{inj}} \quad (14)$$

where S_w no longer includes the fuel system wetted surfaces (note that the area associated with the fuel injection orifices are also not included).

2.3.3.1.8 ENGINE LIFT FORCE

The engine lift force is defined here as the component of the overall force vector parallel to the z coordinate direction which is associated with the pressure and shear force contributions on all engine wetted surfaces from 0 to 6. This is written as follows:

$$F_z = \int_0^6 (P_w \hat{n}_z + \tau_{wz}) dS_w \quad (15)$$

where τ_{wz} is positive when the fluid is moving in the positive z direction.

This can be written in integral form as

$$F_z = \int_0^6 \rho u w dA_0 - \int_6^i (\rho u w dA_6 - \int_0^i (P_b \hat{n}_z + \tau_{bz}) dS_b) - \int_i^6 (P_b \hat{n}_z + \tau_{bz}) dS_b \quad (16)$$

where w is the velocity component in the z direction.

2.3.3.1.9 ENGINE SIDE FORCE

The engine side force (y direction) is defined as the component of the overall force vector which is

parallel to the y axis and which is associated with the pressure and shear force contributions on all engine wetted surfaces from o to 6. This is written as follows:

$$F_y = \int_0^6 (P_w \hat{n}_y + \tau_{wy}) dS_w \quad (17)$$

where τ_{wy} is positive when the fluid motion is in the positive y direction.

This can be written in integral form as

$$F_y = \int_0^6 \rho u v dA_o - \int_6^i \rho u v dA_b - \int_0^i (P_b \hat{n}_y + \tau_{by}) dS_b - \int_i^6 (P_b \hat{n}_y + \tau_{by}) dS_b \quad (18)$$

where v is the velocity component in the y direction.

2.3.3.1.10 DEFINITION OF ENGINE-INDUCED MOMENTS

Each differential pressure and shear force, $d\bar{F}$, on the wetted surface of the engine has a moment arm with respect to the vehicle center-of-gravity (the origin). Let $\bar{R} = x\hat{i} + y\hat{j} + z\hat{k}$ define the moment arm vector. The differential moment is then defined as $\bar{R} \times d\bar{F}$.

The moments about the center-of-gravity (cg) of the vehicle are then given by the following expressions:

Pitch (Positive Nose Up)

$$M_{cg,pitch} = - \int_0^6 (P_w \hat{n}_z + \tau_{wz}) x_{cg} dS_w + \int_0^6 (P_w \hat{n}_x + \tau_{wx}) z_{cg} dS_w \quad (19)$$

Roll (Positive Right Wing Up)

$$M_{cg_{roll}} = - \int\limits_0^6 (P_w \hat{n}_z + \tau_{wz}) y_{cg} dS_w - \int\limits_0^6 (P_w \hat{n}_y + \tau_{wy}) z_{cg} dS_w \quad (20)$$

Yaw (Positive Nose Left)

$$M_{cg_{yaw}} = \int\limits_0^6 (P_w \hat{n}_y + \tau_{wy}) x_{cg} dS_w - \int\limits_0^6 (P_w \hat{n}_x + \tau_{wx}) y_{cg} dS_w \quad (21)$$

2.3.3.1.11 INTEGRAL DEFINITION OF MOMENTS

The moments can also be written in terms of the integrated inflow and outflow plane fluid variables utilizing the moment-of-momentum theorem. The moment-of-momentum theorem for steady flow over the engine control volume is given by:

$$\sum \bar{R}x\bar{F} = \int\limits_S \rho(\bar{R}x\bar{V}) \bar{V} \cdot \hat{n} dS \quad (22)$$

Utilizing this theorem, the following expressions for the engine-induced moments can be derived (note that these are equivalent to equations 19, 20, 21):

Pitch

$$\begin{aligned}
 M_{cg_{pitch}} = & \int_{A_6} [\rho u w x_{cg} - (\rho u^2 + P) z_{cg}] dA_6 - \int_{A_0} [\rho u w x_{cg} - (\rho u^2 + P) z_{cg}] dA_0 \\
 & + \int_0^i (P_b \hat{n}_z + \tau_{bz}) x_{cg} dS_b - \int_0^i (P_b \hat{n}_x + \tau_{bx}) z_{cg} dS_b \\
 & + \int_e^6 (P_b \hat{n}_z + \tau_{bz}) x_{cg} dS_b - \int_e^6 (P_b \hat{n}_x + \tau_{bx}) z_{cg} dS_b
 \end{aligned} \tag{23}$$

Roll

$$\begin{aligned}
 M_{cg_{roll}} = & \int_{A_0} \rho u (y_{cg} w - z_{cg} v) dA_0 - \int_{A_6} \rho u (y_{cg} w - z_{cg} v) dA_6 \\
 & + \int_0^i (P_b \hat{n}_y + \tau_{by}) z_{cg} dS_b - \int_0^i (P_b \hat{n}_z + \tau_{bz}) y_{cg} dS_b \\
 & + \int_e^6 (P_b \hat{n}_y + \tau_{by}) z_{cg} dS_b - \int_e^6 (P_b \hat{n}_z + \tau_{bz}) y_{cg} dS_b
 \end{aligned} \tag{24}$$

Yaw

$$\begin{aligned}
 M_{cg_{yaw}} = & \int_{A_0} \rho u (x_{cg} v - y_{cg} u) dA_0 - \int_{A_6} \rho u (x_{cg} v - y_{cg} u) dA_6 \\
 & + \int_0^i (P_b \hat{n}_x + \tau_{bx}) y_{cg} dS_b - \int_0^i (P_b \hat{n}_y + \tau_{by}) x_{cg} dS_b \\
 & + \int_e^6 (P_b \hat{n}_x + \tau_{bx}) y_{cg} dS_b - \int_e^i (P_b \hat{n}_y + \tau_{by}) x_{cg} dS_b
 \end{aligned} \tag{25}$$

2.3.3.1.12 MEASUREMENT OF ENGINE-INDUCED MOMENTS

This completes the formal comprehensive definition of the moments experienced by a hypersonic vehicle with an airframe-integrated scramjet engine. It follows that there are three ways to measure the moments of the engine:

- a) direct measurement
- b) complete differential description of pressure and shear distributions on all wetted surfaces (internal and external) (equations 19-21)
- c) complete differential description of capture streamtube density, velocity, and pressure on inflow and outflow planes AND complete differential description of pressure and shear force distributions on ALL fluid-fluid interfaces (free-surfaces) of the capture streamtube.
(Equations 23-25)

In the total absence of experimental (or numerical) errors and uncertainties, these three methods yield completely equivalent values of the moments.

2.3.3.1.13 DEFINITION OF MASS CAPTURE

The mass capture of the engine is that air mass flow rate actually processed by the internal configuration of the engine. Referenced to the previous engine diagrams, this mass flow rate is defined based on the mass flux passing through the internal configuration inflow plane, i. e. It is given as follows:

$$\dot{m}_{cap} = \int_i \rho u dA_i \quad (26)$$

2.3.3.1.14 DEFINITION OF FUEL MASS FLOW RATE

The fuel mass flow rate is defined as follows:

$$\dot{m}_{fuel} = - \int_{A_{orifice}} \rho_{fuel} (\vec{V}_{fuel} \cdot \hat{n}) dA_{orifice} \quad (27)$$

Here, ρ_{fuel} is the density of the injected fuel, etc. The unit normal is oriented as previously defined (outward from the engine control volume surface which cuts - in this case - through the plane of the injection orifices).

2.3.3.1.15 DEFINITION OF SPECIFIC THRUST, F_{sp}

Specific thrust is defined as the delivered engine thrust divided by the air mass flow rate captured and processed by the engine:

$$F_{sp} = \frac{F_x}{\dot{m}_{cap}} \quad (28)$$

2.3.3.1.16 DEFINITION OF SPECIFIC FUEL CONSUMPTION, TSFC

TSFC is defined as the total mass flow rate of fuel (in mg/sec) divided by the delivered engine thrust in Newtons:

$$TSFC = \frac{\dot{m}_{fuel}}{F_x} \times 10^6 \quad (29)$$

where \dot{m}_{fuel} has units of kg/sec.

2.3.3.1.17 DEFINITION OF ENGINE SPECIFIC IMPULSE, I_{sp}

Engine specific impulse is defined as the delivered engine thrust divided by the total weight flow rate of fuel:

$$I_{sp} = \frac{F_x}{g_o \dot{m}_{fuel}} \quad (30)$$

where g_o is the sea level gravitational acceleration (9.81 m/s^2), \dot{m}_{fuel} has units of kg/s, F_x has units of Newtons, and specific impulse has units of seconds. Note that I_{sp} is directly proportional to the inverse of the TSFC.

Outline of Section 2.3.4.3

2.3.4.3 Component-Level Derived System Performance

- 2.3.4.3.1 Engine Performance Measures (Definitions)
- 2.3.4.3.2 Engine Performance-Based Assessment of Component Experimental Data
- 2.3.4.3.3 Required Experimental Data for Calculation of Component Performance Contributions and Component-Based Engine Performance
- 2.3.4.3.4 Definition of the Minimum ‘Complete’ Component Experiment
- 2.3.4.3.5 Definition of Minimally Complete Inlet Experiment
- 2.3.4.3.6 Definition of Minimally Complete Combustor Experiment
- 2.3.4.3.7 Component Summary: Experimental Data for Minimally Complete Experiments

2.3.4.3 Component-Level Derived System Performance

The successful design and flight of a hypersonic scramjet-powered vehicle requires the thorough integration and optimization of the propulsion system. Each component in a high-speed jet engine should ultimately be assessed and optimized in terms of maximizing a performance criteria which directly measures the capability of the vehicle to perform an overall mission. This implies that component evaluation and design cannot be separated from either the engine or (ultimately) the vehicle into which the component is to be integrated. Traditional engine component design, however, has not systematically taken into account the synergistic potential which exists when a jet engine (or vehicle) is designed as a single thrust-producing fluid-dynamic device. In this sense, it is erroneous (or at least inaccurate) to state that the ‘function’ of the combustor is to inject, mix, and burn the fuel with the air, and the ‘function’ of the nozzle is to expand the products of combustion and generate thrust. This functional compartmentalization of the various engine components, while convenient, is unfortunate because it usually leads to attempts to analyze and optimize individual components strictly in terms of these specified functions rather than in terms of the performance of the overall engine.

This leads to the following statement of principle when assessing experimental data:

In order to correctly assess performance of a scramjet engine component which is tested experimentally (or modeled analytically/numerically), it is necessary to assess the component within the context of the complete engine design.

The above discussion leads naturally to a single effectiveness definition for engine component design; the effectiveness of an individual engine component, however identified, should be measured solely on the basis of its contribution to overall engine performance. In this broad sense, inlet design and optimization should be done utilizing the same criteria as the combustor, the combustor as the nozzle, etc. This concept, in fact, simply addresses the engine as a single fluiddynamic device rather than as a collection of components which are individually optimized using different performance figures-of-merit. For component design, this requires performance measures which accounts for the synergism between components.

2.3.4.3.1 Engine Performance Measures (Definitions)

At a given vehicle-engine orientation/flight Mach number/altitude, overall scramjet engine performance is defined by the following criteria:

1. engine net thrust (axial force development)
2. engine overall lift (vertical force development)
3. engine overall side-forces (transverse force development)
4. overall moments
5. overall heat load
6. mass flow rate of fuel
7. detailed heating distribution on wetted surfaces (for determination of high heat-transfer regions)
8. engine weight (not considered here)

There are three distinct sets of experimental data which allow the assessment of the above list of overall engine performance criteria:

- a) If i) pressure, shear stress, and heat transfer distributions on ALL wetted surfaces of the engine are known and ii) all inflow (air and fuel) conditions are known – including captured air mass flow rate, then all of the above overall engine performance criteria can be calculated.
- b) If complete (detailed) flow-field characterization of engine ‘entrance’ and engine ‘exit’ planes are known (i.e., pressure, temperature, velocity components, species mass fractions and their spatial distribution on these entrance and exit planes are known), then all the above overall engine performance criteria with the exception of the detailed heating distribution (7) can be calculated. However, for a realistic scramjet engine in which the capture streamtube interacts with external flow both upstream and downstream of the cowl, there are complications with this statement. Nevertheless, it is formally exact for the internal flowpath of the engine and will be useful in the definition of experimental requirements for internal components.
- c) Direct measurement of 1-6 above using force/moment balances, thermal bath, flow meters, etc., on the engine as a whole could be (conceptually) made.

2.3.4.3.2 Performance-Based Assessment of Experimental Data

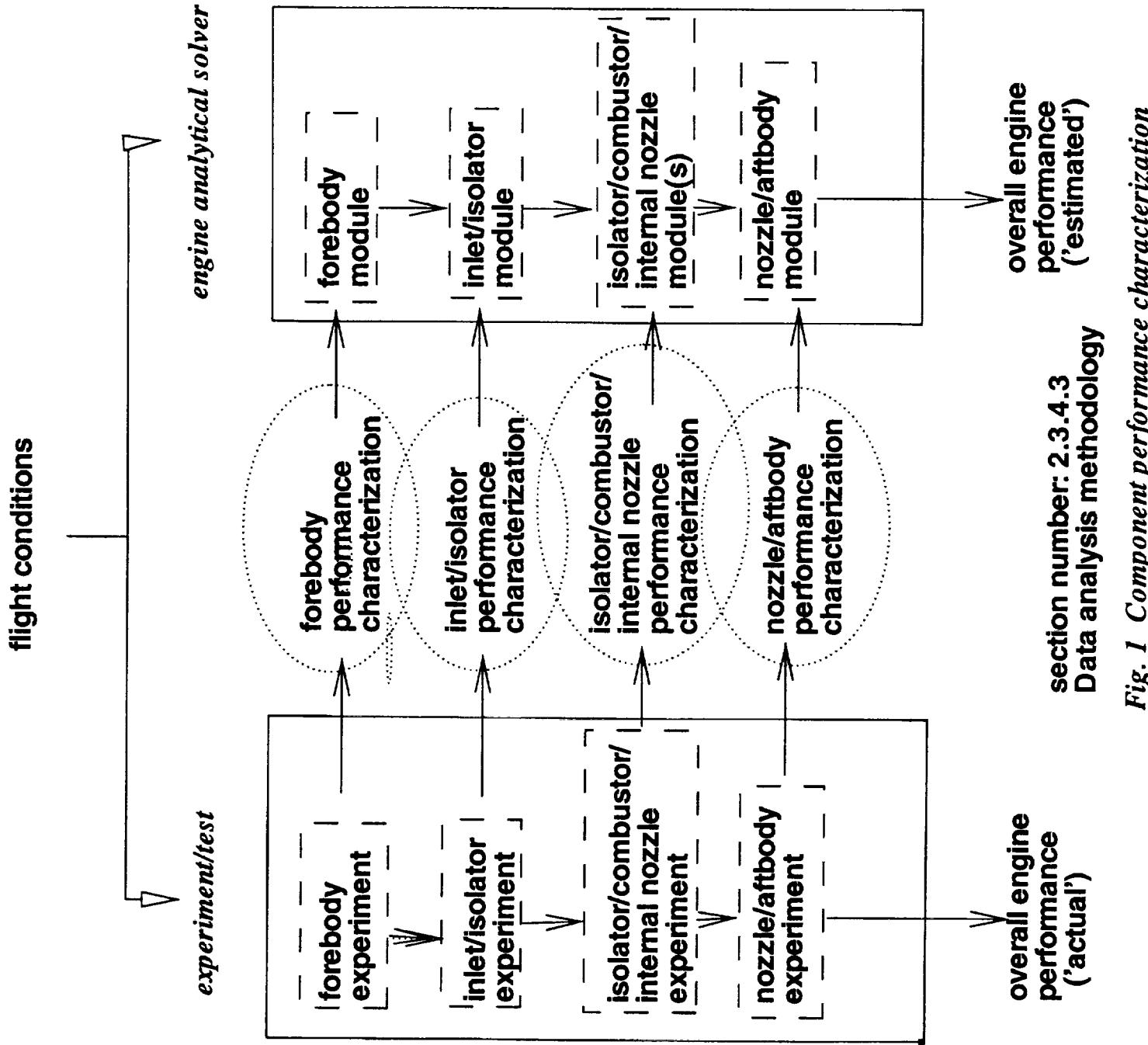
The attached figure (Fig. 1) illustrates the stated principle of system performance-based measurement of component performance and its application in assessing/analyzing component performance from experimental data. The left block represents experiment/testing and is subdivided into various ‘component’ tests. Note that there is (of course) no restriction on testing the entire engine and obtaining ‘true’ engine performance (staying in this left-hand block exclusively). For such a test, the right-hand side (the analytical path) is irrelevant, at least from the standpoint of this discussion.

However, a stand-alone component test requires lateral movement from left to right on this chart. Results of the component test must be correctly characterized in terms of component performance such that these characterizations serve as direct inputs into an engine analytical solver (the right block in the figure). This is done in order to obtain component performance in terms of estimated overall engine performance.

The engine analytical solver (represented by the right block in the figure) can be configured with varying degrees of complexity, ranging from full Navier-Stokes CFD solutions to the simplest cycle solver. The minimum acceptable standard for the analytical solver is a “zero-order” cycle solver. (A zero-order cycle solver is defined in this work as through-engine single-stream analysis conserving mass, momentum, energy and including – as necessary – combustion modeling).

Figure 1 also illustrates the concept of the ‘minimally complete’ component experiment – such an experiment obtains enough characterization of component performance (to be fed as input into the analytical solver) such that the analytical module (right-hand side) in Fig. 1 for that component is unnecessary within the overall analytical solver. This definition does not preclude, however, some accepted level of analysis in the performance characterization of the component.

As will be discussed subsequently, an example of an incomplete combustor experiment would be a combustor experiment with significant heat transfer in which overall forces and moments are measured along with characterization of the degree of combustion at the combustor exit (in some fashion) but overall heat transfer from the component is NOT measured. It is impossible in such a case to completely replace the analytical module for the combustor; one cannot without extensive modeling estimate flux-consistent combustor outflow conditions for input into the downstream nozzle module.



2.3.4.3.3 Required Experimental Data for Calculation of Component Performance Contributions and Component-Based Engine Performance

The following section provides five scenarios for data provided from a generic scramjet component experiment and the resulting ability – or inability – to construct:

- i) actual component contributions to all engine performance parameters (thrust, lift, moments, side force, heating distribution, bulk heating load) as detailed in 2.3.4.3.1
- ii) component exit plane axial fluxes for downstream cycle-code assessment of component-based overall engine performance, and
- iii) distortion information on component exit plane

Note that these five scenarios are not unique; other scenarios can be constructed. However, the five scenarios represent typical experimental data/analysis integration capability. Also note that component lift/side-force/moment balances can be measured by test stand force/moment balances if deemed necessary.

SCENARIO A:

1. Component experimental data provided:

- complete description of inflows
- complete description of exit plane fluid dynamics including species mass fluxes
- $\dot{q}_{\text{wall}}(x, \text{perimeter})$
(η_c on exit plane directly calculable from exit plane information)

2. Component contributions to engine performance which are able to be calculated:

- all (component thrust, lift, sideforce, moments, heating distribution, overall heat load)

3. Component exit plane axial fluxes for estimating component-based engine performance able to be calculated?

- yes (highest fidelity)

4. Component exit plane distortion information available?

- yes

SCENARIO B:

1. Component experimental data provided:

- complete description of inflows
- complete description of exit plane fluid dynamics including species mass fluxes

(η_c on exit plane directly calculable from exit plane information)

2. Component contributions to engine performance which are able to be calculated:
 - all except heating distribution (component thrust, lift sideforce, moments, overall heat load)
3. Component exit plane axial fluxes for estimating component-based engine performance able to be calculated?
 - yes (highest fidelity)
4. Component exit plane distortion information available?
 - yes

SCENARIO C:

1. Component experimental data provided:
 - complete description of inflows
 - $P_{wall}(x, \text{perimeter})$, $\dot{q}_{wall}(x, \text{perimeter})$, $\tau_{wall}(x, \text{perimeter})$
 - ($\eta_c(x)$ obtained by experimental analysis – ‘match’ averaged wall pressure using cycle analysis)
2. Component contributions to engine performance which are able to be calculated:
 - all (component thrust, lift, sideforce, moments, heating distribution, overall heat load)
3. Component exit plane axial fluxes for estimating component-based engine performance able to be calculated?
 - yes
4. Component exit plane distortion information available?
 - no

SCENARIO D:

1. Component experimental data provided:
 - complete description of inflows
 - $P_{wall}(x)$, $\dot{q}_{wall}(x)$, $\tau_{wall}(x)$
 - ($\eta_c(x)$ obtained by experimental analysis – ‘match’ wall pressure using cycle analysis)
2. Component contributions to engine performance which are able to be calculated:

- component thrust, overall heat load, axial heating distribution estimation
(no information on component lift, sideforce, moments)
3. Component exit plane axial fluxes for estimating component-based engine performance able to be calculated?
 - yes
 4. Component exit plane distortion information available?
 - no

SCENARIO E:

1. Component experimental data provided:
 - complete description of inflows
 - overall F_x (thrust balance measure or equivalent)
 - overall \dot{Q} (overall heat load)
 - η_c (exit) estimate from calorimetry
2. Component contributions to engine performance which are able to be calculated:
 - component thrust, overall heat load
(no information on component lift, sideforce, moments, heating distribution)
3. Component exit plane axial fluxes for estimating component-based engine performance able to be calculated?
 - yes
4. Component exit plane distortion information available?
 - no

2.3.4.3.4 Definition of the Complete ‘Minimal’ Experiment

The minimal analytical engine solver (the right block of the figure) has been defined as a zero-order cycle solver. Fundamentally, this level of solver requires inflow overall mass flow rate, inflow stream thrust ($mU + PA$), and inflow total enthalpy flow rate along with a quasi-one-dimensional area description for the downstream components to be analyzed. A skin friction coefficient is used as a loss coefficient; this coefficient properly represents the modeling of all irreversibilities occurring in the flow. A wall temperature distribution is also used (usually in conjunction with the Reynolds Analogy) to model heat transfer from the component. In addition, for combustor modeling (relevant for inlet tests), fuel mass flow rate, momentum, and total enthalpy as well as some information allowing the assessment of the degree of combustion is necessary in order to model reaction effects in the flow.

Therefore, the MINIMAL requirement for a complete component experiment is that the results of the experiment, suitably characterized with an acceptable amount of analysis, allow the subsequent downstream calculation (estimation) of the engine flowpath performance using the minimal analytical engine solver, i.e., the zero-order cycle solver. This implies that the experimental data, as a minimum, must include overall axial force on the component, overall heat load, and a combustion efficiency estimate, if relevant.

Note that this definition does not utilize flow distortion information; this then represents an inevitable uncertainty associated with distortion as far as final performance (as estimated by the analytical solver) is concerned. Furthermore, such a definition of the minimal requirement also prioritizes the overall engine performance criteria (see the initial list); for example, the detailed heating distribution information in the component is simply NOT necessary in order to meet this particular definition of the minimal experiment. Furthermore, information relevant to moments and out-of-axial forces may be missing from the experimental results for the minimal complete experiment (as defined above). Downstream calculations at this minimal level are not dependent on such information – any final estimates of overall engine out-of-axial forces and moments would be incomplete without such information, however. Hence, this is TRULY a “MINIMAL” definition; minimal does not equate with desirable or even necessarily acceptable, depending on specific requirements.

The following provides brief discussions of what is considered to be the minimal experimental information for a ‘complete’ component test.

2.3.4.3.5 Minimally Complete Inlet Experiment

In the quasi-one-dimensional context of this discussion, the inlet is a variable-area duct with heat transfer and shear on surfaces and with internal irreversibilities.

The minimal information from an experiment which allows calculation of the necessary fluxes for subsequent engine analysis using a zero-order cycle solver is as follows:

- i) adequate inflow conditions (mass flow rate m_{air})
- ii) overall inlet axial force measurement, F_x
- iii) overall heat transfer, \dot{Q}

From this information, one-dimensional inlet exit conditions can be computed which satisfy mass, momentum, and enthalpy fluxes and the gas equation of state. The engine analytical cycle solver can then be used to estimate the component performance in terms of overall engine performance.

Note that F_x may be found from comprehensive measurement of the spatial distribution of wall pressures and wall shear stresses or from a force balance on the entire component. Similarly, \dot{Q} can be found from comprehensive measurement of the spatial distribution of wall heat transfer or from a bulk measure of the heat transferred from the component.

The (possibly critical) effects of flow distortion are neglected. Such effects can drive actual downstream combustor component performance. Additionally, if bulk measurements of force and heat are made, information on local heating and on component moment and out-of-axial force contributions to the overall engine are not available. In addition, real gas effects are not considered in this minimal view.

2.3.4.3.6 Minimally Complete Combustor Experiment

From the quasi-one-dimensional standpoint, the combustor is considered as a variable-area duct with heat transfer and shear on surfaces and with internal irreversibilities. Additionally, there are mass, momentum, and energy additions associated with fuel injection at some axial location(s) within the component. There is some axial distribution of individual species mass fluxes due to combustion (i.e., some species mass fluxes increase while others decrease) which correspond to the so-called ‘heat-release’ of exothermic combustion. Note, however, that the combustion process does NOT represent the addition of energy across the boundary as heat, i.e., it does not correspond to the Rayleigh heat addition process. It simply represents an internal transfer of energy within the flow/fluid from chemical (molecular) modes to translational modes.

The minimal information from a combustor experiment which allows calculation of the necessary fluxes for subsequent engine analysis using a zero-order cycle solver is as follows:

- i) adequate inflow conditions definition (including injection conditions)
- ii) overall inlet axial force measurement, F_x
- iii) overall heat transfer, \dot{Q}
- iv) estimate of major species mass fluxes at exit plane (i.e., combustion efficiency, η_c)

From this information, one-dimensional combustor exit conditions can be computed which minimally satisfy mass, momentum, and enthalpy fluxes and the gas equation of state. The engine analytical solver can then be used in order to estimate the combustor performance in terms of the overall engine performance.

As noted for the inlet, F_x can be obtained either from a force balance on the component or from adequate measurement of the spatial variation of the static pressure and wall shear stresses on wetted surfaces. Similarly, \dot{Q} can be obtained from either a global measurement or a detailed spatial (integrated) measurement.

An estimate of the major species mass fluxes at the combustor exit plane (or at intermediate axial location within the combustor) can be obtained from the experimental wall pressure data (actually an adequate one-dimensional representation of the wall pressure data) by varying combustion efficiency within an analytical solver over the combustor itself until analytical wall pressures match experimental wall pressures. This process, however, represents the introduction of the analytical solver into the component data characterization process itself (the middle interface of the figure); the combustion efficiency obtained in such a fashion (regardless of how high-level the analytical technique is which is used in obtaining it) is NOT experimental data, but instead represents a combination of experimental and analytical results. Alternatively, the combustion efficiency can be found using experimental calorimetry. Again, this requires analysis.

As noted for the inlet, the effects of flow distortion at the combustor exit are completely neglected when a zero-order analytical solver is used for downstream computations. Additionally, information on local heating and on component moment and out-of-axial force contributions may be neglected as well.

2.3.4.3.7 Component Summary for Experimental Data (Minimally Complete Experiment)

The following chart represents the requirements for data from component experiments which allows a minimum-level ‘complete’ analysis of the component-based performance of the engine in terms of a cycle-level engine analysis (level 0).

engine stations	0 – 1.0	1.0 – 2.2	2.2 – 5.5
forebody		inlet/isolator	<u>isolator/combustor/nozzle</u>
	$F_x(\int P_x dS, \int \tau_{w_x} dS)$	$F_x(\int P_x dS, \int \tau_{w_x} dS)$	$F_x(\int P_x dS, \int \tau_{w_x} dS)$
	\dot{Q}	\dot{Q}	\dot{Q}
	free stream conditions	inflow conditions (1.0) including \dot{m}_{air}	inflow conditions including fuel conditions
	exit flow conditions at 1.0 including \dot{m}_{cap} at 1.0		η_c (major species mass fraction fluxes or ratios)
	5.5 – 6.0		
	<u>external nozzle/afterbody</u>		
		$F_x(\int P_x dS, \int \tau_{w_x} dS)$	
		\dot{Q}	

2.3.4.2 MODELING ANALYSIS AND SIMULATION

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2.3.4.2 MODELING ANALYSIS AND SIMULATION

2.3.4.2.1 OVERVIEW OF ENERGY CONSIDERATION FOR SCRAMJET ENGINES

Considering the streamtube shown in Fig. 2, we can write the first law for the scramjet engine as follows:

$$\dot{H}_{t_{\text{outflow}}} = \dot{H}_{t_{\text{inflow}}} + \dot{H}_{t_{\text{fuel injection}}} + \dot{Q}_{\text{walls}} + \dot{Q}_{\text{free surfaces}} \quad (1)$$

where

$$\text{i) } \dot{H}_{t_{\text{outflow}}} = \int_{\text{outflow}} \rho u \left\{ \sum_{\ell=1}^{\text{NCS}} \alpha_\ell (h_{t_\alpha}) + \int_{T_{\text{ref}}}^T C_{p\ell} dT + \frac{u^2 + v^2 + w^2}{2} \right\} dA_{\text{outflow}} \quad (2)$$

$$\text{ii) } \dot{H}_{t_{\text{outflow}}} = \int_{\text{outflow}} \rho u \left\{ \sum_{\ell=1}^{\text{NCS}} \alpha_\ell (h_{t_\alpha}) + \int_{T_{\text{ref}}}^T C_{p\ell} dT + \frac{u^2 + v^2 + w^2}{2} \right\} dA_{\text{inflow}} \quad (3)$$

and α_ℓ = mass fraction of species ℓ

NCS = total number of species present

h_{t_α} = reference enthalpy at T_{ref}

$C_{p\ell}$ = specific heat of species ℓ

$$\text{iii) } \dot{H}_{t_{\text{fuel injection}}} = - \int_{\text{fuel orifices}} \rho (\vec{V}_{\text{inj}} \cdot \hat{n}) \left\{ h_{t_{\text{of fuel}}} + \int_{T_{\text{ref}}}^{T_{\text{fuel}}} C_{p_{\text{fuel}}} dT + \frac{\vec{V}_{\text{inj}} \cdot \vec{V}_{\text{inj}}}{2} \right\} dA_{\text{orifice}} \quad (4)$$

$$\vec{V}_{\text{inj}} = u_{\text{inj}} \hat{i} + v_{\text{inj}} \hat{j} + w_{\text{inj}} \hat{k} \quad (5)$$

iv)
$$\dot{Q}_{\text{walls}} = \int_{S_w}^{(6)} \dot{q}_w dS_w$$

where \dot{q}_w is the heat rate per area
transferred into fluid from the wetted
surface of the engine

(6)

v)
$$\dot{Q}_{\text{free surfaces}} = \int_{S_b}^{(6)} \dot{q}_b dS_b$$

where \dot{q}_b is the heat rate per area
transferred into fluid from the
surrounding fluid interfaces

(7)

2.3.4.2.2 OVERVIEW OF SECOND-LAW CONSIDERATIONS FOR SCRAMJET ENGINES

The fundamental statement of the second law of thermodynamics for the streamtube processed by the scramjet engine is as follows:

$$\dot{S}_6 = \dot{S}_o + \dot{S}_{\text{fuel}} + \dot{S}_{\substack{\text{reversible} \\ \text{heat} \\ \text{transfer}}} + \dot{S}_{\text{irr}} \quad (8)$$

where:

\dot{S}_6 = entropy per second passing through outflow plane

\dot{S}_o = entropy per second passing through inflow plane

\dot{S}_{fuel} = entropy per second passing through fuel injection orifice

$\dot{S}_{\substack{\text{reversible} \\ \text{heat} \\ \text{transfer}}}$ = entropy per second associated with all heat transfer from all boundaries to the fluid in the control volume

$$= \dot{S}_{\substack{\text{reversible} \\ \text{heat transfer}(S_w)}} + \dot{S}_{\substack{\text{reversible} \\ \text{heat transfer}(S_b)}}$$

and

\dot{S}_{irr} = entropy per second generated inside the central volume due to irreversible mechanisms within the control volume. These irreversible mechanisms are as follows:

- a) friction between adjacent streamtubes
- b) heat transfer between adjacent streamtubes
- c) (diffusive) mass transfer between adjacent streamtubes
- d) non-equilibrium chemical reactions
- e) shocks also associated with a) and b)

By definition,

$$\dot{S}_{\text{plane}} = \int_{\text{plane}} \rho u \left(\sum_{\ell=1}^{\text{NCS}} \alpha_{\ell} s_{\ell} \right) dA_{\text{plane}} \quad (9)$$

where

$$s_{\ell} = s_{o\ell} + \int_{T_{\text{ref}}}^T C_{p\ell} \frac{dT}{T} - r_{\ell} \frac{P}{P_{\text{ref}}} - r_{\ell} \ell n X_{\ell} \quad (10)$$

with $s_{o\ell}$ = reference entropy at $T_{\text{ref}}, P_{\text{ref}}$ of species ℓ

r_{ℓ} = gas constant for species ℓ

X_{ℓ} = mole fraction of species ℓ .

2.3.4.2.3 MINIMUM-LEVEL CYCLE CODE DESCRIPTION AND REQUIRED INPUTS

The following equations and discussion summarize the minimum requirements for a cycle code simulation of a scramjet engine including required inputs for the simulation. Note that individual components may not require the level of detail embedded within these equations: i.e., a mixing efficiency distribution would not be generally required in a nozzle simulation. However, in the interest of generality, all terms relevant to a complete engine simulation are included here.

$$1. \quad d(\rho u A) = d\dot{m}_{fuel}$$

$$d(\rho u^2 A + PA) = - \int_{S_w} P \hat{n}_x dS_w - \int_{S_{inj}} P_{inj} \hat{n}_x dS_{inj}$$

2.

$$- \frac{1}{2} \rho u^2 C_f c dx + u_{inj} d\dot{m}_{fuel}$$

Note that $\bar{V}_{fuel} = u_{inj} \hat{i} + v_{inj} \hat{j} + w_{inj} \hat{k}$ (See Fig. 6)

$$3. \quad d \left\{ \rho u A \left[\sum_{\ell=1}^{NCS} \alpha_\ell (h_{t_\ell} + \int_{T_{ref}}^T C_{p\ell} dT) + \frac{u^2}{2} \right] \right\} \\ = d\dot{m}_{fuel} \left[h_{to_{fuel}} + \int_{T_{ref}}^{T_{fuel}} C_{p_{fuel}} dT + \frac{\bar{V}_{fuel} \cdot \bar{V}_{fuel}}{2} \right] + \frac{C_f}{2} \rho u C_{p_{mix}} (T_w - T_{aw}) c dx$$

$$\text{where } T_{aw} = T + \frac{ru^2}{2C_{p_{mix}}} \quad (r = \text{recovery factor})$$

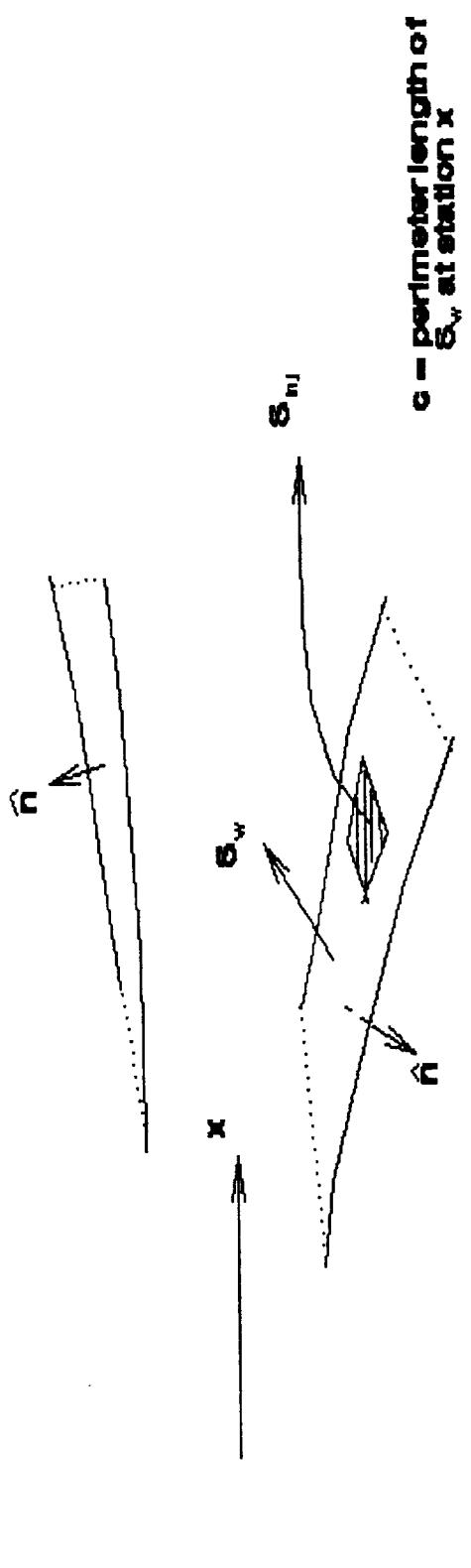


Figure 6: Injection geometry

4. $P = \rho RT$ where $R = \frac{R_{\text{univ}}}{mW_{\text{tot}}}$

and $mW_{\text{tot}} = \frac{1}{\sum_{\ell=1}^{NCS} \frac{\alpha_\ell}{mW_\ell}}$ {mw = molecular weight}

5. $d(\alpha_\ell) = \frac{\dot{w}_\ell dx}{\rho u}$

where \dot{w}_ℓ = mass of species ℓ produced per unit time per unit volume (at P, T) due to chemical reactions.

\dot{w}_ℓ is properly evaluated using finite-rate kinetics (i.e., non-equilibrium kinetics). Finite-rate chemistry is inclusive of the limits of both equilibrium chemistry and frozen chemistry. Equilibrium chemistry is approached when \dot{w}_ℓ approaches zero (due to forward rate and backward rate equality). Frozen chemistry approached as u becomes very large such that $d(\alpha_\ell)$ approaches zero; the time scale (dx/u) associated with fluid dynamic transport across dx is then much smaller than the time scale associated with relaxation of chemical equilibrium.

Finite-rate chemistry calculations automatically develop a progressive combustion efficiency distribution with x ($\eta_c(x)$) due to the kinetics. For problems which are mixing-limited, an externally developed mixing efficiency distribution, $\eta_m(x)$, can be input in order to provide an upper 'mixing' limit on the degree of combustion at any x station. For such problems, \dot{w}_ℓ is simply set to zero when and if $\eta_c(x) \geq \eta_m(x)$.

The change in mass fractions $d(\alpha_i)$ can also be evaluated using complete reaction (in which all available reactants go to products). Without external (imposed) control, reaction would simply be instantaneous, i.e., no $\eta_c(x)$ distribution would be developed. Therefore, the technique of complete reaction demands an input 'mixing' efficiency, $\eta_m(x)$, as an upper limit on the degree of combustion such that $\eta_c(x) = \eta_R \eta_m(x)$. Here η_R is an input 'reaction efficiency'. Such a method simply limits ('schedules') the heat of reaction or equivalently limits ('schedules') the formation of products.

Required inputs or models for MINIMUM 1-D cycle code solutions for scramjet engine are as follows:

1. full geometry definition; including injector locations and sizes
2. characteristic one-dimensional inflow conditions; inclusive of mass capture
3. characteristic one-dimensional fuel inflow conditions; inclusive of fuel mass flow rate
4. 'average' skin friction coefficient distribution based on $\tau_w = C_f \frac{1}{2} \rho u^2$
5. major inflow constituents (mass fractions for inflow)
6. recovery factor; recovery factor distribution
7. adequate finite-rate reaction mechanisms/model i.e., 'adequate' reactions/ 'adequate' species, including finite-rate reaction constants
8. 'average' wall temperature distribution
9. mixing efficiency distribution
10. reaction efficiency (for complete reaction-based solvers)
11. adequate thermodynamic curve fits for all major species across temperature range encountered in engine